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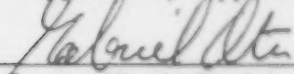
10.6 μm AEROSOL EXTINCTION COEFFICIENT MEASURED WITH THE PVM
FORWARD SCATTER METER

by

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SANS CLASSIFICATION

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ABSTRACT

Knowledge of the aerosol extinction coefficient at infrared wavelengths is necessary for predicting the performance of electro-optical systems such as thermal imagers. Recently, Gerber Scientific Inc. has developed an instrument that makes a local measurement of the aerosol extinction coefficient at a wavelength of $10.6\ \mu\text{m}$. It exploits the strong correlation observed between visible light forward scattered between 0.3 and 3.6° and the infrared extinction coefficient. We report field measurements made with this instrument in a wide variety of atmospheric conditions. The results compare favorably with transmissometer measurements of extinction in the $10\text{-}12\ \mu\text{m}$ band and are consistent with extinction derived from measured aerosol size spectra.

RÉSUMÉ

La connaissance du coefficient d'atténuation des aérosols dans l'infrarouge est nécessaire à la prévision du rendement de systèmes électro-optiques comme les imageurs thermiques. Gerber Scientific Inc. a récemment mis au point un appareil permettant de mesurer localement le coefficient d'atténuation des aérosols à une longueur d'onde de $10,6\ \mu\text{m}$. Cet appareil met à profit la forte corrélation observée entre la dispersion vers l'avant dans le visible entre $0,3$ et $3,6$ degrés, et le coefficient d'atténuation dans l'infrarouge. Des mesures effectuées sur le terrain dans différentes conditions atmosphérique à l'aide de cet appareil sont rapportées. Les résultats se comparent favorablement aux mesures d'atténuation dans la bande $10\text{-}12\ \mu\text{m}$ effectuées à l'aide d'un transmissomètre et correspondent à l'atténuation dérivée des mesures de la distribution granulométrique des aérosols.

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EXECUTIVE SUMMARY

Extinction by atmospheric aerosols and molecular species can greatly attenuate visible and infrared (IR) radiation and therefore limit the performance of electro-optical (EO) systems such as thermal imagers, IR search and track systems and laser rangefinders. The molecular extinction can be modelled with great accuracy with computer codes such as LOWTRAN or MODTRAN using local meteorological conditions as inputs. However, the extinction due to aerosols is much more difficult to obtain due to their high spatial and temporal variability. Currently available aerosol models are generalizations that cannot give the IR aerosol extinction accurately at a particular time or place. Therefore, for timely information on local IR extinction, measurements of *in situ* aerosol characteristics may provide the additional inputs needed for the prediction of EO system performance.

A new family of optical instruments is available to measure IR aerosol extinction and other aerosol microphysical properties. The instruments, known as Particulate Volume Monitors (PVM), measure the intensity of visible light forward scattered between 0.3 and 3.6° which has been shown to be highly correlated with the infrared extinction coefficient of haze, cloud and fog aerosols. In this document we report on experiments to verify the performance of one of these instruments, the PVM-300 which measures the aerosol extinction coefficient at $10.6\text{ }\mu\text{m}$. We found that the PVM-300 is a superior sensor for monitoring IR extinction and is much more autonomous than aerosol spectrometers, the only other type of instrument capable of providing IR aerosol extinction. Because of its ease of use and calibration, and its relatively high temporal resolution, the PVM-300 is ideally suited for validation of aerosol models and could be used on the battlefield or aboard ships for real-time assessment of aerosol IR extinction.

1.0 INTRODUCTION

Predicting the performance of electro-optical systems requires an assessment of the atmospheric extinction coefficient. In the infrared (IR), molecular extinction can be calculated to good accuracy using available models and knowledge of the atmospheric temperature, pressure and humidity. However, the extinction due to aerosols cannot be easily obtained through models because of the high spatial and temporal variability characteristic of aerosols. Therefore, for many applications, aerosol extinction must be measured. Gerber Scientific Inc. has developed an instrument that makes a local measurement of the aerosol extinction coefficient at a wavelength of $10.6\ \mu\text{m}$ ($\alpha_a(10.6\ \mu\text{m})$). The device, called the Particulate Volume Monitor (PVM), measures the intensity of visible light forward scattered between 0 and 3.6° which has been shown to be highly correlated with the infrared extinction coefficient of water droplet clouds and fogs.

We compare measurements of $\alpha_a(10.6\ \mu\text{m})$ made with the PVM during fog conditions to extinction derived from measurements of transmittance in the 10 to $12\ \mu\text{m}$ spectral band. An analysis of fog models shows that the effective band-averaged extinction coefficient derived from the transmission measurements should be within 10% of $\alpha_a(10.6\ \mu\text{m})$. The results show that there is generally good agreement between the PVM and transmissometer derived extinction coefficients. However, the effect of spatial averaging over the $100\ \text{m}$ path of the transmissometer causes a significant amount of scatter between them. We also present measurements made with the PVM on an ocean platform during the MAPTIP experiment which show that it is robust enough for routine use in the harsh marine environment and is ideally suited for monitoring IR aerosol extinction.

This work was carried out at DREV from May 1993 to Dec. 1995 under PSC 32E15 "EO Battlefield Surveillance/Atmospheric Propagation Studies".

2.0 THE PVM EXTINCTION SENSOR

The PVM are a family of instruments that provide microphysical data on haze and fog aerosols. The PVM-300 used in our experiments is designed to measure the IR aerosol extinction coefficient at $10.6\ \mu\text{m}$. A detailed description of the PVM-300 and the theory of operation and calibration are given in Refs. 1-3. A photograph of the PVM-300 is shown in Fig. 1. The PVM-300 consists of a collimated laser diode transmitter with a wavelength of $780\ \text{nm}$ and a coaxial receiver located at a distance of $42\ \text{cm}$. The beam irradiates a

volume of approximately 3 cm^3 . At the center of the receiver is a light trap that intercepts the unscattered beam. Light that is forward scattered from the beam by ambient aerosols passes the light trap and is collected by the receiver in the angular range of approximately 0.3 to 3.6° . At the focal plane of the receiver lens is a circular variable light transmission filter (spatial filter) and just beyond that a large-area silicon photodiode detector. The spatial filter renders the scattered intensity contributions from aerosols of a given size to be proportional to their extinction cross section at a wavelength of $10.6 \text{ }\mu\text{m}$. The total forward scattered signal is thus proportional to the total aerosol extinction cross section or the extinction coefficient at $10.6 \text{ }\mu\text{m}$. So, by measuring the intensity of visible light forward scattered by aerosols, an estimate of the extinction coefficient of those aerosols at $10.6 \text{ }\mu\text{m}$ is obtained.

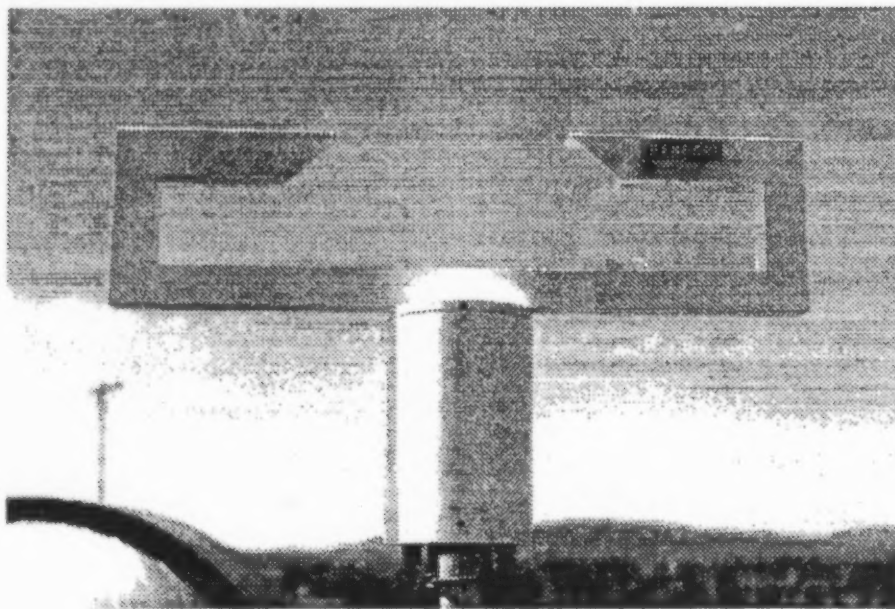


FIGURE 1 - Photograph of the PVM-300 aerosol sensor. The length of the instrument is 85 cm

The aerosol extinction coefficient near $10.6 \text{ }\mu\text{m}$ has been shown to be approximately proportional to the liquid water content (LWC) of clouds and fog (Refs. 4 and 5) and a different spatial filter in the instrument yields an output proportional to LWC from which the name particulate volume monitor is derived. To calibrate the PVM-300 for the measure-

ment of $\alpha_a(10.6 \mu\text{m})$ the instrument output was compared to aerosol extinction derived from a narrow band transmissometer with peak spectral response at $10.6 \mu\text{m}$. The calibration tests were made by the manufacturer in the presence of haze and cloud droplets produced in an environmental chamber. On the basis of this comparison, the accuracy of the PVM was determined to be $\pm 10\%$ with a precision of $\pm 0.05 \text{ km}^{-1}$. One of the sources of error for the PVM-300 is that the IR extinction efficiency used to calculate the transmittance profile of the spatial filter depends on the index of refraction of the particles at the wavelength of interest. Since the index of refraction depends on the type and composition of the aerosol, the spatial filter was designed for a representative aerosol, the Maritime haze model of Shettle and Fenn (Ref. 6) at a relative humidity of 80%. However, the calibration against the transmissometer, made in the presence of a wide variety of haze and cloud types, shows that the PVM can be used to measure $\alpha_a(10.6 \mu\text{m})$ for most types of naturally occurring hazes or liquid water clouds.

3.0 IR TRANSMISSOMETER

A transmissometer was built at DREV to provide the band-averaged transmittance in 10 to $12 \mu\text{m}$ spectral band from which an effective aerosol extinction can be derived. The transmissometer source was a blackbody at a temperature of 650°C collimated to 6 cm radius using an off-axis parabolic mirror with a half-angle beam divergence of 5 mrad. The receiver consists of a 7.6 cm radius off-axis parabolic mirror which focuses the radiation onto a MCT detector. There is a 10 to $12 \mu\text{m}$ band pass filter just in front of the detector. The receiver half-angle field of view is 3.0 mrad. The wavelength-weighted peak spectral response (λ_o) of the transmissometer is $10.8 \mu\text{m}$ where λ_o is defined as

$$\lambda_o = \int_{\lambda_1}^{\lambda_2} \lambda R(\lambda) d\lambda \quad (1)$$

In Eq. 1, $R(\lambda)$ is the transmissometer spectral response shown in Fig. 2 and λ_1 and λ_2 are the limits of the transmissometer spectral band. $R(\lambda)$ is the product of the source spectral emittance, the receiver band pass filter function and the detector responsivity. $R(\lambda)$ is normalized such that

$$\int_{\lambda_1}^{\lambda_2} R(\lambda) d\lambda = 1. \quad (2)$$

Specifications of the IR transmissometer are summarized in Table I.

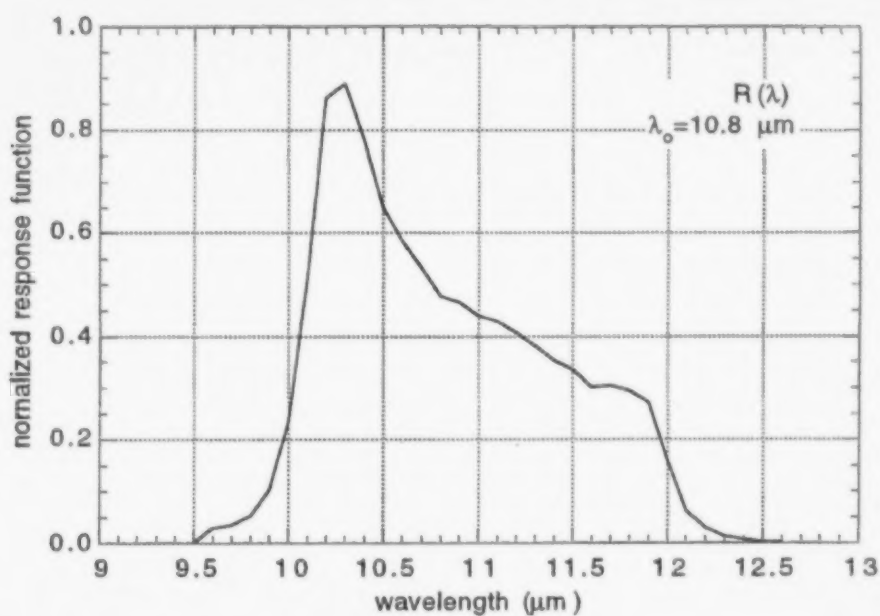


FIGURE 2 - DREV IR transmissometer spectral response.

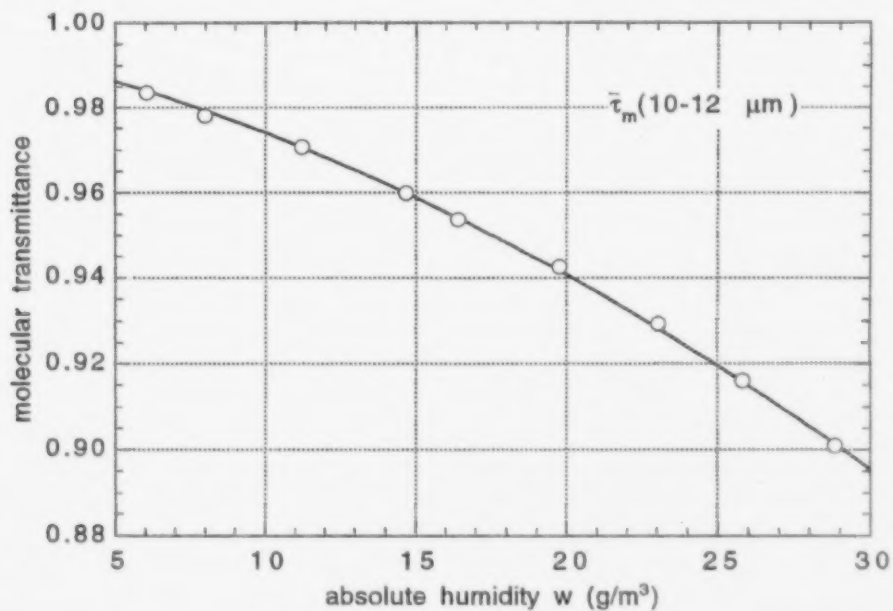


FIGURE 3 - Band averaged transmittance due to molecular absorption for a 100 m path

TABLE I
DREV IR transmissometer characteristics

Blackbody source temperature	650° C
Path length	100.0 m
Source collimator radius	6.0 cm
Source 1/2 angle divergence	5.0 mrad
Receiver objective radius	7.6 cm
Receiver 1/2 angle field of view	3.0 mrad
Spectral band	10-12 μm
Peak spectral response	10.8 μm
Estimated accuracy	±3%

The quantity we seek is $\bar{\tau}_a(\lambda_1, \lambda_2)$, the effective band averaged transmittance component due to aerosol extinction and scattering. It is defined as

$$\bar{\tau}_a(\lambda_1, \lambda_2) = \frac{\int_{\lambda_1}^{\lambda_2} R(\lambda) \tau_a(\lambda) \tau_m(\lambda, w) d\lambda}{\int_{\lambda_1}^{\lambda_2} R(\lambda) \tau_m(\lambda, w) d\lambda} = \frac{\bar{\tau}(\lambda_1, \lambda_2)}{\bar{\tau}_m(\lambda_1, \lambda_2, w)} \quad (3)$$

where $\tau_a(\lambda)$ is the spectral transmittance due to absorption and scattering by the aerosols and $\tau_m(\lambda, w)$ is the spectral transmittance due to molecular absorption. $\tau_m(\lambda, w)$ is a function of both wavelength and the ambient water vapor concentration or absolute humidity w . In Eq. 3, the numerator is the total band averaged transmittance and the denominator is the transmittance component due to molecular absorption.

LOWTRAN7 (Ref. 7) was used to calculate $\tau_m(\lambda, w)$ for the 100 m path length of the transmissometer and for different temperatures and relative humidities. The integral in the denominator of Eq. 3 was then evaluated for each $\tau_m(\lambda, w)$ curve and the results parameterized in terms of w which is given by (Ref. 8),

$$w(\text{g/m}^3) = H A \exp(18.9766 - 14.9595 A - 2.4388 A^2) \quad (4)$$

where H is the relative humidity expressed as a number between 0 and 1 and $A = 273.15/(273.15 + T)$, T being the temperature in degrees Celsius. The resulting curve is shown in Fig. 3.

The signal measured by the transmissometer is

$$P = k \int_{\lambda_1}^{\lambda_2} R(\lambda) \tau_a(\lambda) \tau_m(\lambda, w) d\lambda \quad (5)$$

where k is an instrument constant. k is obtained using Eq. 5 during clear weather when the presence of aerosols may be assumed to be negligible. Assuming that $\tau_a(\lambda)=1$, we have

$$k = \frac{P_c}{\int_{\lambda_1}^{\lambda_2} R(\lambda) \tau_m(\lambda, w_c) d\lambda} = \frac{P_c}{\bar{\tau}_m(\lambda_1, \lambda_2, w_c)} \quad (6)$$

In Eq. 6, P_c is the transmissometer signal measured during a clear period and $\bar{\tau}_m(\lambda_1, \lambda_2, w_c)$ is the molecular transmittance for the absolute humidity w_c during the clear period. The total band averaged transmittance $\bar{\tau}(\lambda_1, \lambda_2)$ defined in Eq. 3 can be expressed in terms of measured quantities by combining Eqs. 5 and 6,

$$\bar{\tau}(\lambda_1, \lambda_2) = \frac{P}{P_c} \bar{\tau}_m(\lambda_1, \lambda_2, w_c) \quad (7)$$

Finally, combining Eqs. 3 and 7 yields the desired effective aerosol extinction as determined from the transmissometer signals P and P_c and the calculated molecular transmittances $\bar{\tau}_m(\lambda_1, \lambda_2, w_c)$ and $\bar{\tau}_m(\lambda_1, \lambda_2, w)$:

$$\bar{\tau}_a(\lambda_1, \lambda_2) = \frac{P \bar{\tau}_m(\lambda_1, \lambda_2, w_c)}{P_c \bar{\tau}_m(\lambda_1, \lambda_2, w)} \quad (8)$$

An effective aerosol extinction coefficient representative of the spectral band of the transmissometer is determined from $\bar{\tau}_a(\lambda_1, \lambda_2)$ using the Bouguer-Beer-Lambert law:

$$\bar{\alpha}_a(\lambda_1, \lambda_2) = -\ln[\bar{\tau}_a(\lambda_1, \lambda_2)]/z \quad (9)$$

4.0 EFFECT OF AEROSOL TYPE ON BAND-AVERAGED IR EXTINCTION

The extinction coefficient of aerosols varies considerably as a function of wavelength within the 10 to 12 μm spectral band. This is illustrated in Fig. 4 which shows the extinction coefficient of the four fog models of Ref. 6 and the maritime models with 99% and 80% relative humidity plotted as a function of wavelength. The extinction values of each model are normalized by the values at 10.6 μm . Figure 4 shows that the variation of extinction with wavelength depends on the aerosol type. Therefore, the band-averaged extinction derived from the transmissometer measurements will depend in an unpredictable way on the aerosol type. This introduces an error when comparing $\bar{\alpha}_a(\lambda_1, \lambda_2)$ from the transmissometer to $\alpha_a(10.6 \mu\text{m})$ derived from the PVM. To calculate the effect of the spectral shape of the aerosol extinction on $\bar{\alpha}_a(\lambda_1, \lambda_2)$, the spectral transmittance of the aerosol models was calculated for a path of 100 m and multiplied by the transmissometer response $R(\lambda)$. The band-averaged aerosol transmittance was then calculated using

$$\bar{\tau}_a(\lambda_1, \lambda_2) = \int_{\lambda_1}^{\lambda_2} R(\lambda) \tau_a(\lambda) d\lambda \quad (10)$$

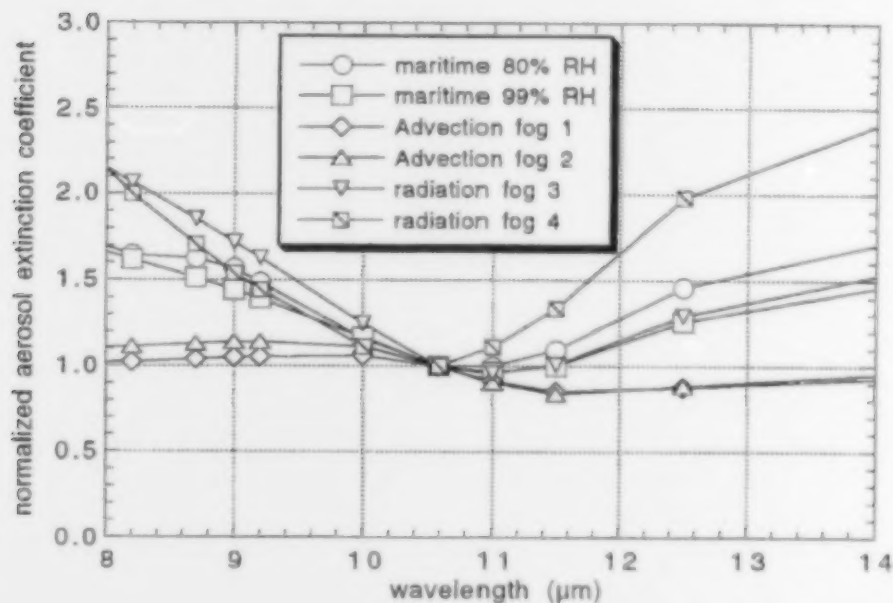


FIGURE 4 - Extinction of fog haze and models normalized by the extinction coefficient at 10.6 μm

The resultant transmittance for each aerosol model was transformed to effective extinction $\bar{\alpha}_a(\lambda_1, \lambda_2)$ using Eq. 9. The ratio of $\alpha_a(10.6 \mu\text{m})$ to $\bar{\alpha}_a(\lambda_1, \lambda_2)$ for each model is shown in Table II.

The average value of the ratio of $\alpha_a(10.6 \mu\text{m})$ to $\bar{\alpha}_a(\lambda_1, \lambda_2)$ given in Table II is 0.98 with a standard deviation of 0.08. During the experiments no information was available about the size distribution or type of aerosol so the variations given in Table II represent a possible difference of $\pm 7\%$ between the transmissometer and PVM measurements. A more elaborate error analysis could be done by including a larger number of aerosol models and weighting them by their probability of occurrence, if it were known. However the figure of $\pm 7\%$ derived from Table II is sufficient to give an idea of the relationship between $\alpha_a(10.6 \mu\text{m})$ and $\bar{\alpha}_a(\lambda_1, \lambda_2)$. In any case, the results of Table II show that the transmissometer is at least as accurate as the PVM instrument we are studying.

TABLE II

Extinction ratios for fog and haze aerosol models

Fog model	$r_{\text{eff}} (\mu\text{m})$	$\frac{\alpha_a(10.6\mu\text{m})}{\alpha_a(0.55\mu\text{m})}$	$\frac{\alpha_a(10.6\mu\text{m})}{\alpha_a(\lambda_1, \lambda_2)}$
Advection fog 1	20	1.16	1.07
Advection fog 2	16	1.11	1.06
Radiation fog 3	6	0.55	0.96
Radiation fog 4	3	0.22	0.86
Maritime 99%	0.75	0.37	0.97
Maritime 80%	0.32	0.153	0.94

5.0 EFFECT OF FORWARD SCATTERING ON TRANSMISSOMETER

We checked the possibility that multiple forward scattering could influence the IR transmittance measurements. For this we used the multiple scattering propagation model of Bissonnette (Ref. 9) to calculate the ratio of scattered to unscattered received power. Using the specifications of the transmissometer given in Table I, the calculations were carried out with the advection fog 1 and radiation fog 3 aerosol models from Ref. 6. The multiple scattering model requires the scattering function of the aerosols which were calculated for

10.6 μm using the index of refraction of water given in Hale and Querry (Ref. 10) and using the Mie computer code of Bohren and Huffman (Ref. 11). The ratio of scattered received power to unscattered received power was less than 0.01% for the radiation fog 3 model and below 0.1% for the advection fog 1 model for extinctions up to 100 km^{-1} . This shows that the effect of scattering on the 10-12 μm transmittance measurements is negligible in fog.

6.0 RESULTS

Measurements were made with the PVM and transmissometer in July 1993 during periods of advection fog which formed over the Gulf of St. Lawrence. The fog extended west over 20 km inland to our measurement site at the Defence Research Establishment Valcartier (DREV). At DREV the fog was dissipating and was in the form of intermittent patches. The PVM and transmissometer receiver were located on the roof of a laboratory building approximately 11 m above ground level. The transmissometer source was on another building 100 m from the receiver and at the same elevation. The transmissometer path was aligned at an angle of 100° degrees measured with respect to North. During the fog episodes the wind was usually from the West with a typical speed of 5 km/h. The optical axis of the PVM was aligned North-South so as to keep the receiver pointing North and avoid the possibility of sunlight being scattered into the receiver. The time constant of the PVM was 1 s but the analog output of the instrument was averaged continuously with a 10 s time constant by the data acquisition system. The output of the transmissometer detector was synchronously demodulated using a lock-in-amplifier with a 10 s time constant. Valid data was obtained for three fog episodes on July 12, 14 and 20, 1993.

Figure 5 shows a time plot of IR aerosol transmittance $\bar{\tau}_a(10-12 \mu\text{m})$ measured during one of the fog episodes. $\bar{\tau}_a(10-12 \mu\text{m})$ was derived from the raw transmissometer signal using Eq. 8. In Fig. 6, $\bar{\tau}_a(10-12 \mu\text{m})$ has been transformed to $\bar{\alpha}_a(10-12 \mu\text{m})$ using Eq. 9 where it is plotted with $\alpha_a(10.6 \mu\text{m})$ measured simultaneously with the PVM. The overall correlation between the two extinction measurements is excellent. The PVM extinction exhibits considerably more variability than that of the transmissometer. This is attributed to the effect of spatial averaging of the transmissometer signal. During the measurements, the average wind speed was less than 1 m/s and was approximately parallel to the transmissometer beam and perpendicular to the optical axis of the PVM. Low wind velocity perpendicular to the PVM axis means that wind induced turbulence and shadowing effects have little

or no influence on the PVM measurement. Also, considering that the two instruments were recorded with the same time constant, spatial averaging of the measured transmittance is the only possible explanation for $\bar{\alpha}_a(10-12 \mu\text{m})$ having much less temporal variability than $\alpha_a(10.6 \mu\text{m})$.

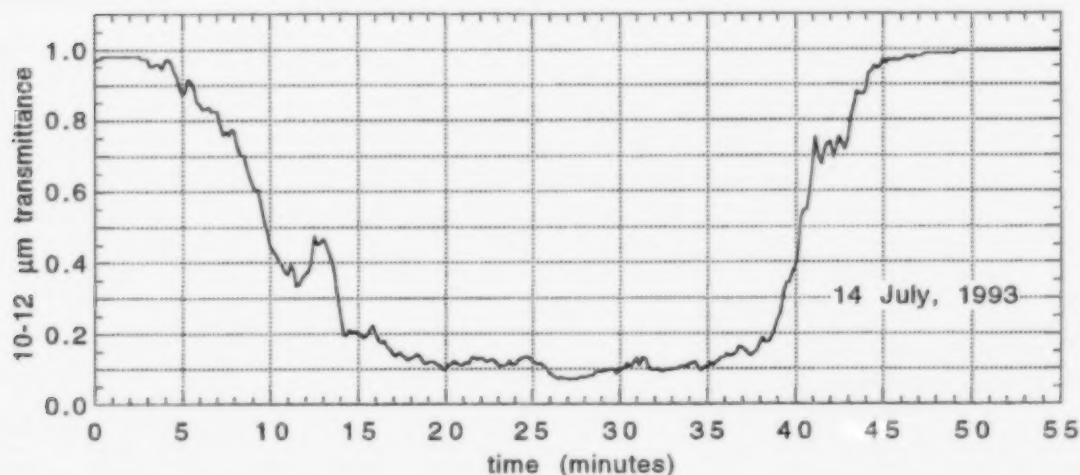


FIGURE 5 - Time plot of IR transmittance measured at DREV on 14 July, 1993

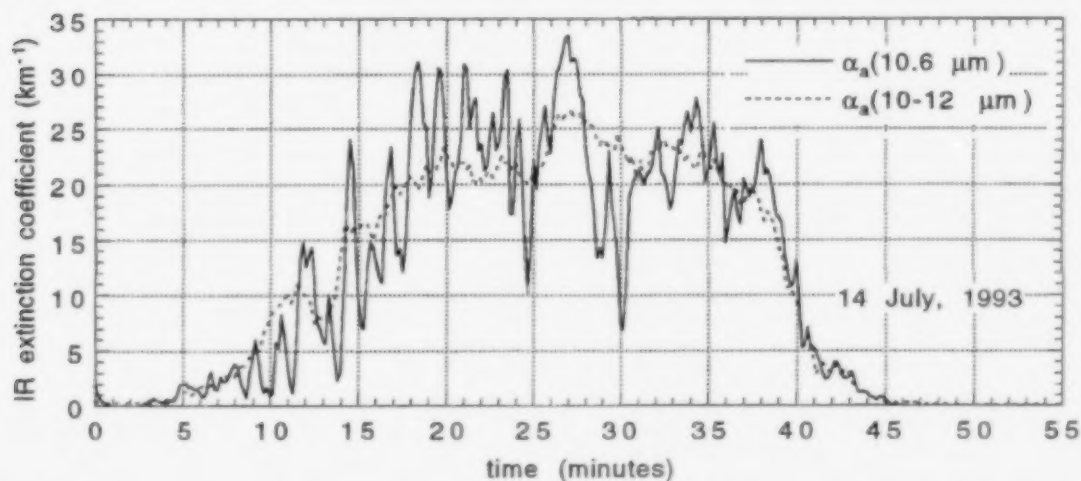


FIGURE 6 - Time plot of aerosol extinction coefficient derived from the transmissometer and PVM

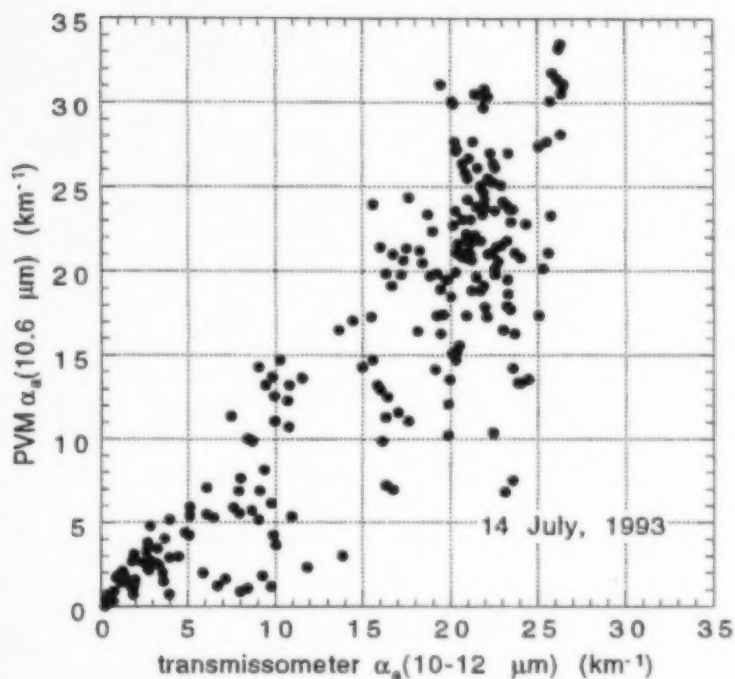


FIGURE 7 - Scatter plot of PVM and transmissometer extinction measured July 14, 1993

The PVM extinction is plotted as a function of the transmissometer extinction in Fig. 7. A linear regression on the data yields a slope of 0.995 with a correlation coefficient of 0.89. The slope being near unity is somewhat fortuitous considering the scatter among the points and the discussion of Section 4.0, where it was shown that the ratio of $\bar{\alpha}_a(10-12 \mu\text{m})$ to $\alpha_a(10.6 \mu\text{m})$ could vary by $\pm 7\%$ depending on the aerosol droplet size distribution. Regression slopes for the two other fog episodes on July 12 and 20 were 1.36 and 0.926 respectively with similar correlation coefficients. The scatter plots for these other episodes are shown in Figs. 8 and 9.

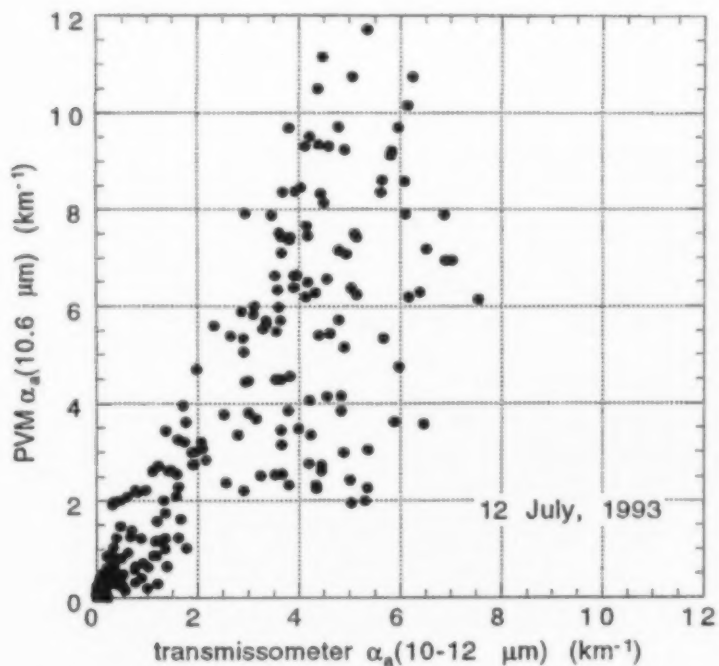


FIGURE 8 - Scatter plot of PVM and transmissometer extinction measured July 12, 1993

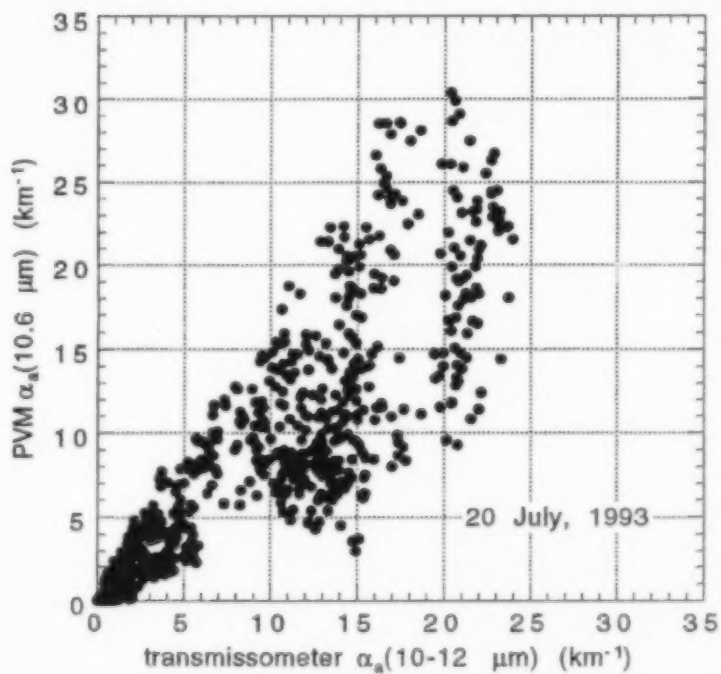


FIGURE 9 - Scatter plot of PVM and transmissometer extinction measured July 20, 1993

7.0 COMPARISON OF VISIBLE AND IR AEROSOL EXTINCTION

Table II gives the ratio of aerosol extinction at $10.6\text{ }\mu\text{m}$ to the extinction at $0.55\text{ }\mu\text{m}$ as well as the effective radius corresponding to some of the Shettle and Fenn (Ref. 6) aerosol models. The table shows that aerosols with small radii have IR extinctions much less than in the visible. For aerosols with larger radii, such as dense fogs, the extinction at 10.6 and $0.55\text{ }\mu\text{m}$ are similar. The extinction at $10.6\text{ }\mu\text{m}$ can even surpass that at $0.55\text{ }\mu\text{m}$ for fogs with very large droplet radii such as the advection fog 1 model. Although there is no general relation between IR and visible extinction, the fogs with large droplet radii are associated with high extinction coefficients. Therefore visible and IR extinction coefficients should be similar for high extinction conditions and the IR extinction should be lower than the visible extinction when the extinction is low. This trend was observed during all our measurements. For example, Fig. 10 shows a time plot of IR extinction measured with the PVM and visible extinction measured with a forward scatter visibility meter. The visibility meter was a model VR-301 manufactured by HSS Inc., Bedford MA. The PVM and visibility meter were located close to each other near the transmissometer receiver. The visibility meter had a time constant of 10 s. As expected, the visible extinction is higher than the extinction at $10.6\text{ }\mu\text{m}$ for most of the plot but they are nearly equal for the peaks of extinction greater than 30 km^{-1} .

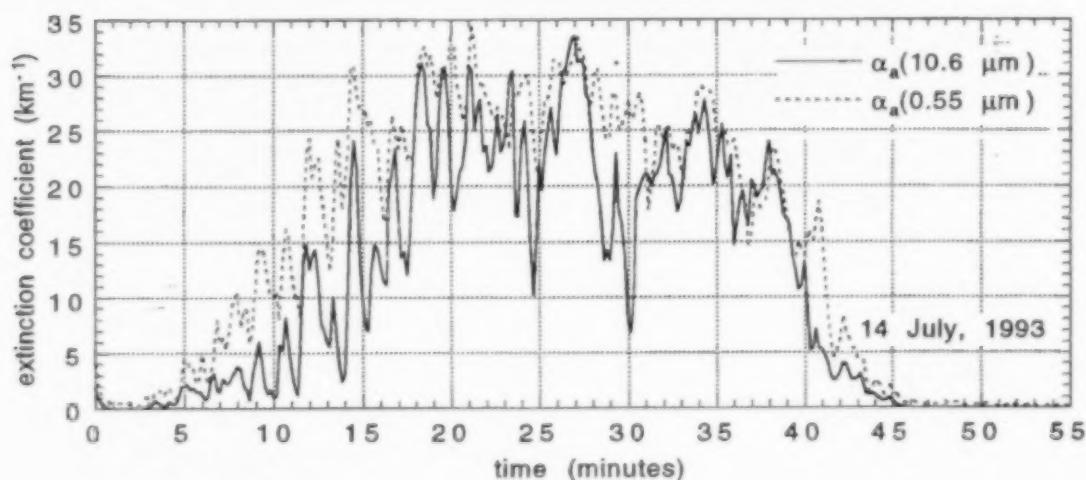


FIGURE 10 - Time plot of aerosol extinction at $10.6\text{ }\mu\text{m}$ measured with the PVM and at $0.55\text{ }\mu\text{m}$ measured with the HSS visibility meter

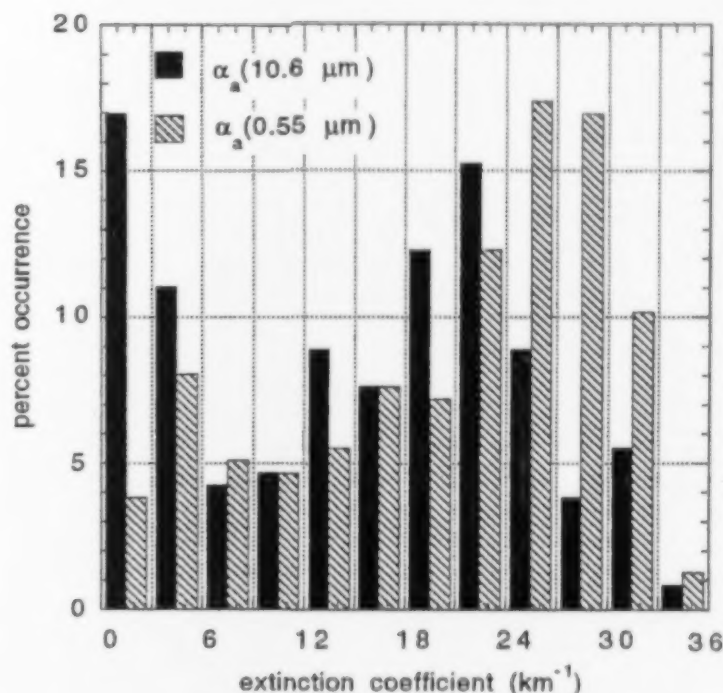


FIGURE 11 - Histogram of IR (PVM) and visible extinction measured July 14, 1993

Figure 11 shows a frequency histogram of the visible and IR extinction data of Fig. 10. The distribution of the visible extinction coefficient data set is clearly skewed toward higher extinctions while the distribution of the IR extinction is skewed toward lower extinction. The occurrence frequency of the highest extinction values is nearly the same for both the visible and IR. This is what we would expect on the basis of typical fog microstructure where higher extinction is associated with larger mean droplet radius. These results are a good indication that the PVM gives a valid measure of the local IR extinction coefficient. Furthermore, the fact that the IR aerosol extinction cannot be derived from the visible extinction without information about the droplet size distribution shows that the PVM provides valuable and unique information for characterizing the IR propagation environment.

8.0 MAPTIP MEASUREMENTS

The Marine Aerosol Properties and Thermal Imager Performance (MAPTIP) experiment (Ref. 12) was sponsored by NATO Panel 4 Research Study Groups 5 and 8. MAPTIP took place from 11 October to 5 November 1993, with most of the activities based at the ocean platform Meetpost Noordwijk (MPN) off the Dutch coast at position $45^{\circ} 16' 25.9''$ N, $04^{\circ} 17' 45.8''$ E. The MPN platform is shown in Fig. 12. One of the goals of the MAPTIP program was to provide aerosol microphysical and extinction data for the validation of marine aerosol models. The PVM-300 and a HSS VF-500 visibility meter were used by DREV at the MPN platform to provide IR and visible aerosol extinction data during the experiment.



FIGURE 12 - MPN platform used during MAPTIP experiment, Oct. to 5 Nov. 1993 in the North Sea off the Dutch coast

Figures 13 and 14 show time plots of 1-hour averages of $10.6\ \mu\text{m}$ and visible aerosol extinction measured with the PVM and HSS sensors during the trial. The data illustrate the high degree of variability and the complex relationship between IR and visible extinction characteristic of marine boundary layer aerosols. Also shown in Figs. 13 and 14 are the $10.6\ \mu\text{m}$ and visible aerosol extinction predicted by the Navy Aerosol Model (NAM) currently used in LOWTRAN7, evaluated using the consensus MAPTIP meteorological data as input (Ref. 13).

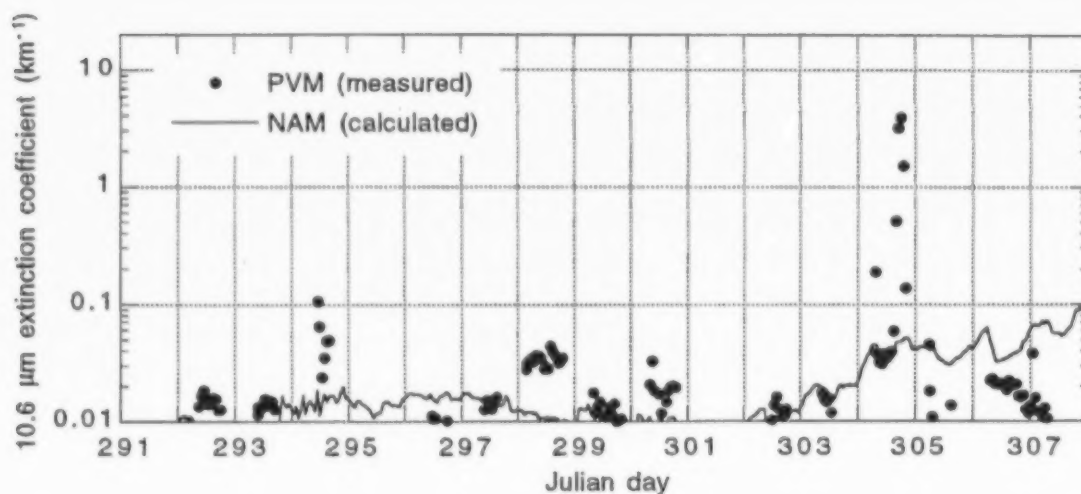


FIGURE 13 - 10.6 μm aerosol extinction measured with the PVM-300 (1 hour averages) and calculated with the Navy Aerosol Model (NAM)

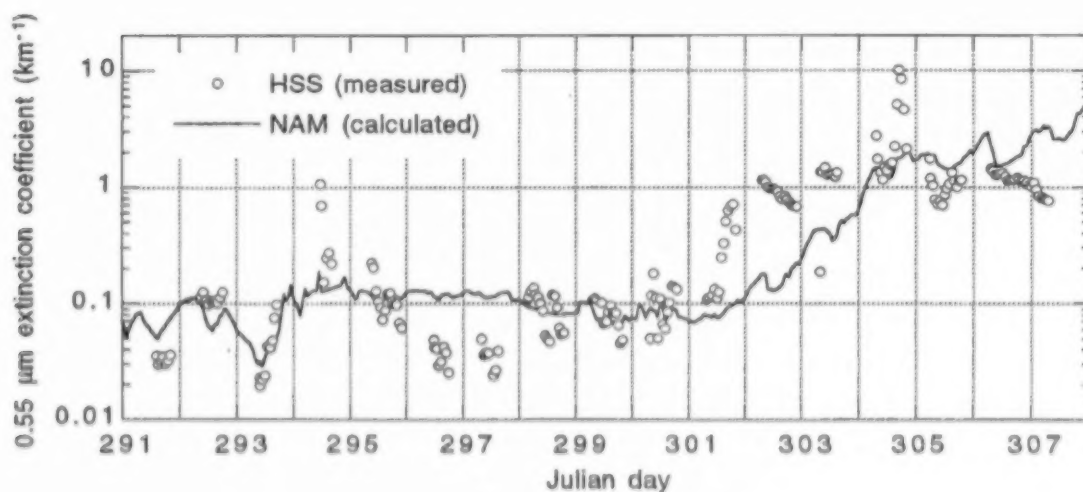


FIGURE 14 - Visible aerosol extinction measured with HSS VF-500 (1 hour averages) and calculated with NAM

The results of Figs. 13 and 14 show that the aerosol extinction predicted by NAM is within an order of magnitude of the measurements for most of the data set except during the fog episode on day 304 (Oct 31). However, for many applications such as EO system performance prediction, the accuracy afforded by the NAM model is insufficient. More sophisti-

cated models are currently under development but meaningful validation of models over the full range of weather conditions from very clear air to fog, as encountered during the MAPTIP trial, require convenient means of measuring aerosol extinction.

The aerosol extinction coefficient depends upon the concentration, size distribution and composition of the aerosols. Direct measurements of these quantities were made on the MPN platform by several groups from which the visible and IR extinction coefficients were calculated. In particular, aerosol spectrometers manufactured by Particle Measuring Systems, Boulder CO were used by University of Manchester Institute of Science and Technology (UMIST), TNO Physics and Electronics Laboratory (TNO) and NRaD, San Diego. The interpretation and correction of the aerosol spectrometer data is discussed in detail in Ref. 13. Intercomparison of visible and 10.6 μm extinction coefficient derived from the aerosol spectra measured by the various groups showed that there were difficulties with the calibration and performance of aerosol spectrometers (Ref. 13). Another difficulty with the interpretation of the aerosol spectra is the long integration time required. Under most conditions, integration times of 20 to 30 minutes are required to generate a smooth aerosol size spectrum.

Figure 15 shows a scatter plot of 10.6 μm aerosol extinction calculated from aerosol size spectra independently measured by the three groups at MAPTIP, plotted against 10.6 μm aerosol extinction measured with the PVM-300. Although the extinction derived from the aerosol size spectra correlates poorly with the PVM data, the correlation is no worse than between the TNO, UMIST and NRaD data itself. Therefore, there is no evidence that the PVM data is any worse than that derived from aerosol spectrometer data, yet the PVM data is much more easily obtained.

The accuracy of extinction coefficient measured during clear-air conditions is lower for both aerosol spectrometers and the PVM-300. Truncation error is more significant and the uncertainty of the aerosol refractive index more pronounced for interpreting aerosol size spectra measured during clear air conditions. The PVM suffers low signal to noise ratio during clear air.

For foggy conditions, the PVM is better suited for monitoring extinction than are the aerosol spectrometers because the PVM can follow rapid changes in the extinction that are lost to the aerosol spectrometers due to their long integration time. Also, the PVM is much

easier to calibrate and does not suffer from air flow uncertainty, coincident particle counts, and "dead time" error caused when two droplets pass through the aerosol sample chamber at the same time or a droplet passes through while the spectrometer is busy resetting its registers (Refs. 14, 15). These errors may be significant in aerosol spectra if the cloud droplet concentration is very high as it is during fog conditions. Significant errors in the aerosol spectra may also be caused by the limited electronic response time of the spectrometer and inhomogeneity of the laser beam (Ref. 16).

One disadvantage of the PVM compared to aerosol spectrometers is that the PVM does not provide detailed information on the aerosol size distribution. However, for many applications the desired quantity is just the IR aerosol extinction. So the PVM provides a simple means of measuring this important parameter and at a much higher temporal resolution than is possible with aerosol spectrometers.

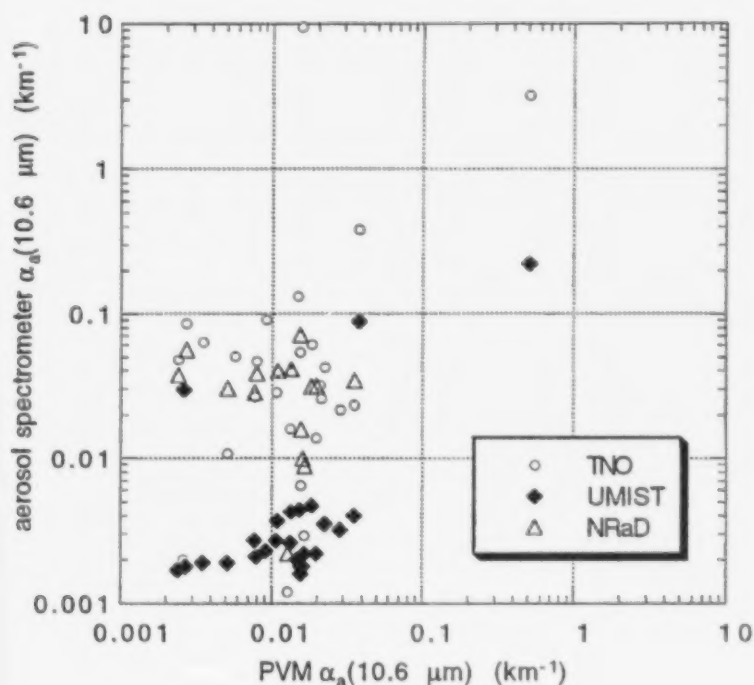


FIGURE 15 - 10.6 μm aerosol extinction calculated from aerosol size spectra plotted against extinction measured with the PVM-300

9.0 CONCLUSIONS

We compared measurements of $\alpha_a(10.6 \mu\text{m})$ made with a Particulate Volume Monitor (PVM) in fog to extinction derived from measurements of transmittance in the 10 to 12 μm spectral band. An analysis of fog models showed that the effective band averaged extinction coefficient derived from the transmission measurements could differ from $\alpha_a(10.6 \mu\text{m})$ by up to $\pm 7\%$. The PVM has a rated accuracy of $\pm 10\%$ and the transmissometer has an estimated accuracy of 3%. Therefore, assuming random errors, we would expect the PVM and transmissometer derived extinction coefficients to be within $\pm 13\%$ of each other. The results showed that on average, the PVM and transmissometer extinction were within $\pm 10\%$ of each other for two of three fog episodes measured. Linear regressions on PVM extinction versus transmissometer extinction yielded slopes of 0.995 and 0.926. For a third episode the linear regression yielded a slope of 1.36. The correlation coefficients for the regressions were between 0.85 and 0.89. Spatial averaging of the extinction along the 100 m transmissometer path is believed to be responsible for much of the scatter between the simultaneously measured PVM and transmissometer signals.

Comparison of the PVM extinction to visible extinction measured with a HSS visibility meter showed that the visible and IR extinction become nearly equal for high extinction levels in agreement with the optical properties of standard fog models. Since both the PVM and HSS instruments provide a local measurement, this comparison does not suffer from the influence of spatial averaging encountered with the transmissometer measurements. Therefore, in spite of the limitations imposed by spatial averaging, the results show that there is generally good agreement between the PVM and transmissometer and that the PVM provides realistic values of $\alpha_a(10.6 \mu\text{m})$ when compared to visible extinction measurements.

Data provided by the PVM during the MAPTIP experiment show that the instrument is a valuable tool for validation of marine aerosol models due to its ease of use and high temporal resolution. There is no evidence that the PVM measurements are more or less accurate than extinction derived from aerosol size spectra during most conditions, but during fog, the PVM is a superior sensor for monitoring IR extinction and is much more autonomous than the aerosol spectrometers. Based on the measurements described here, we conclude that the PVM is a valuable tool for monitoring local IR aerosol extinction.

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Knowledge of the aerosol extinction coefficient at infrared wavelengths is necessary for predicting the performance of electro-optical systems such as thermal imagers. Recently, Gerber Scientific Inc. has developed an instrument that makes a local measurement of the aerosol extinction coefficient at a wavelength of 10.6 μm . It exploits the strong correlation observed between visible light forward scattered between 0.3 and 3.6° and the infrared extinction coefficient. We report field measurements made with this instrument in a wide variety of atmospheric conditions. The results compare favorably with transmissometer measurements of extinction in the 10-12 μm band and are consistent with extinction derived from measured aerosol size spectra.

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